EXPERIMENTAL STUDY OF DIFFUSER CHANNELS WITH PRESEPARATION STATE OF THE TURBULENT BOUNDARY LAYER

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EXPERIMENTAL STUDY OF DIFFUSER CHANNELS WITH PRESEPARATION STATE OF THE TURBULENT BOUNDARY LAYER

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ABSTRACT. Experimental study of preseparation diffuser channels of circular cross section. The geometrical and aerodynamic characteristics of the channels are determined as functions of the degree of initial inhomogeneity of the flow on the basis of a semiempirical method of calculating the turbulent boundary layer, starting from the condition that the flow is at the preseparation stage. The calculation is performed with an accuracy equal to that of the empirical constant figuring in the determination of the mixing path length. The velocity profiles are measured on models of diffusers of circular cross section in a number of cross sections, on the basis of which the nominal areas of the boundary layer are calculated.

Results are presented of an experimental study of the aerodynamic characteristics of diffusers whose longitudinal section variation provides the preseparation state of the turbulent boundary layer. It is shown that the experimental results agree with the calculations. /518*

The selection of optimal diffuser longitudinal section variation makes it possible to provide maximal flow deceleration

*Numbers in the margin indicate pagination in the original foreign text.

in a given length. Experimental studies of conical diffusers show that in the separation-free flow region the total pressure losses in the diffuser decrease with increase of the expansion angle as long as flow separation does not take place at any section [1]. Thus, the best pressure recovery is achieved in the flow regime preceding separation and the losses increase markedly with onset of separation.

It is natural to suppose that one possible technique for reducing the losses duirng flow deceleration is to profile the diffuser walls so that the flow will be quite close to separation at every section of the channel (surface friction $\tau_w = 0$). The channel whose flow section variation is selected on the basis of this condition will have optimal aerodynamic characteristics. This idea was suggested by Loitsyanskiy in the 30's [2]. The contour of the two-dimensional or circular-section diffuser with a preseparation boundary layer, the so-called "preseparation" diffuser, has a bell-like shape. In the entrance portion of the channel, when the boundary layer is relatively thin, the local divergence angles may be large, then as the boundary layer thickens the angles must decrease so as to maintain maximal capability of the flow to overcome the local pressure gradient without separation along the entire diffuser length.

Preseparation turbulent flow past a plane wall was realized in [3, 4]; it was found that such flow is quite stable. It was shown in [5, 6] that bell-like diffusers profiled on the basis of conditions close to those corresponding to the preseparation state of the boundary layer are in many cases more efficient than diffusers with straight walls and separation-free flow. Here the improvement may be in either decrease of the losses for fixed channel length or shortening of the axial dimensions for a given value of the efficiency.

An approximate method for calculating the geometric and aerodynamic characteristics of preseparation diffusers of plane and circular cross section was described in [2]. The method is based on the well-known relations for plane and axisymmetric separating turbulent boundary layers [7]. It is nautral that use of the very simple approximate method for calculating the turbulent boundary layer leads to a situation in which the final results obtained are quite approximate. However, it is possible to identify the basic nature of the relationships characteristic of diffusers with preseparation flow. The use of more complex theories would hardly be justified. This is due, first of all, to the fact that such theories are very approximate even in the two-dimensional boundary layer case, and theories have not yet been devised for the axisymmetric turbulent preseparation layers which take complete account for the influence of transverse surface curvature. /519

In the theoretical study of preseparation diffusers in [2] the following assumptions were made: the flow is incompressible, the pressure is constant across the channel, and the turbulent boundary layer is of the preseparation type along the entire length ($\tau_W = 0$). We shall write out the formulas obtained in [2] for determining the characteristics of the initial flow segment (with the presence of a potential core) of circular cross-section diffusers:

expansion ratio

$$n = \frac{1}{\bar{u}_\delta}\left\{1 - \Delta_0^*\left[1 - \frac{H}{H_0}\bar{u}_\delta^{-[1+0,5(H+H_0)]}\right]\right\},$$

velocity outside the boundary layer 5

$$\bar{u}_\delta = u_\delta/u_{\delta 0} = \Phi^\beta ,$$

$$\beta = [1 + 0,5(H + H_0)]^{-1}, \quad \Phi = \frac{1}{1-\Delta_0^*}\cdot\frac{2\bar{\delta}_0 - \bar{\delta}_0^2}{2\bar{\delta} - \bar{\delta}^2}\cdot\frac{H_0^{**}}{H^{**}} - \frac{H}{H_0}\Delta_0^*,$$

total pressure loss coefficient

$$\zeta = \frac{\Delta^{***}}{n^2(1-\Delta^*)^3} - \frac{\Delta_0^{***}}{(1-\Delta_0^*)^3}$$

as the function of the longitudinal coordinate ξ,

$$\xi = k^2 x/r_{w0} = -4 \int_1^{\bar{u}_\delta} \frac{\bar{\delta}\sqrt{n}}{\bar{u}_\delta P^2}, \quad P = \sqrt{\bar{\delta}}/E(\varphi_\delta;\ \theta).$$

Here k is the experimental constant in the expression for the mixing length $l = ky$, $E(\varphi_\delta;\ \theta)$ is the elliptical integral of the second kind with argument $\varphi_\delta = \arcsin\sqrt{\bar{\delta}}$ and modulus $\cos\theta = \sqrt{2}/2$; $\Delta = \theta/F$; $\Delta^* = \theta^*/F$; $\Delta^{**} = \theta^{**}/F$; $\Delta^{***} = \theta^{***}/F$; $H = \Delta^*/\Delta^{**}$; $H^{**} = \Delta^{**}/\Delta$; $\bar{\delta} = \delta/r_w$.

The calculation method is approximate, since it is based on very simple approximations for the distribution of the friction and mixing length across the boundary layer. The theoretical-computational analysis is simplified considerably by the assumption that the turbulent boundary layer is of the preseparation type along the entire length of the channel, including the entrance section. However, in reality, if separation is not induced at the entrance preseparation flow can be realized only to /520
some distance from the entrance. In the latter case there will be a segment in which the flow will be transformed from the separation-free type to the preseparation type. The presence of such a transitional segment may lead to dependence of the channel aerodynamic characteristics on the entrance Reynolds number. However, in the case of completely preseparation flow the Reynolds number does not influence the boundary layer and therefore does not affect the diffuser characteristics.

It follows from the formulas presented above that the geometric and aerodynamic characteristics of preseparation diffusers depend on the single parameter Δ_0^*, which expresses the influence of the initial flow nonuniformity at the entrance. In fact, it follows from the discharge equation that this parameter determines uniquely the ratio of the mean and maximal velocities at the entrance section

$$\Delta_0^* = 1 - \frac{u_0}{u_{\delta 0}}.$$

The relations obtained are valid for $\Delta_0^* > 0$, and becomes meaningless for $\Delta_0^* = 0$, since in this case preseparation flow at the entrance is not possible.

The calculation results showed that with increase of the initial nonuniformity the diffuser expansion ratio decreases for a given length and the loss coefficient increases.

In order to construct the diffuser contour we need to know the magnitude of the experimental constant k. This constant appears as a factor in the value of the longitudinal coordinate ξ, which makes possible qualitative determination of the basic relations governing the variation of the preseparation diffuser characteristics even when the value of the experimental constant is not known.

The value of k was found tentatively from analysis of the very limited amount of experimental data available concerning both preseparation flows over a wall and in a channel, and was then refined in the process of the experiment. Change of the value of k simply deforms the longitudinal coordinate uniformly. Comparison of our calculated relationships with the corresponding data of Stratford [3] and Nestler [8] yielded the value k = 0.325 - 0.400. Taking the smaller value of k in the calculation, we stretch the diffuser out somewhat and eliminate the danger of separation occurring; however, in this case preseparation flow may not be realized. When selecting larger values of k, we can construct a more efficient diffuser with preseparation flow; however, in this case the danger of the onset of strong separation increases. The difficulty in studying preseparation diffusers of circular cross section lies in the fact that the model geometry is not amenable to correction in the course of the experiment. This circumstance makes it difficult to correct errors in the calculation and bring the flow regime closer to the preseparation regime. Therefore, for a given initial flow nonuniformity, when profiling the model we first selected the smaller of the k values for which the theory agrees with the available experimental data. Then this model was modified so that its contour corresponded to that calculated with larger k, which made it possible to establish the value of the empirical constant corresponding to maximal flow deceleration over a fixed length.

When calculating channels with a thin boundary layer at the entrance, the theoretical values of the local expansion angles $[\alpha/2 = 0.5 \operatorname{arctg}(\Pi^{-1} dF/dx)]$ are excessively large $(\alpha/2 > 10°)$. In such cases, the area where the diffuser joins the inlet duct is smoothed somewhat $(\alpha/2 \leqslant 9°)$ in order to reduce the negative influence of the corner point (which is not taken into account within the framework of boundary layer theory). This corresponds to reduction of the peaks in the local expansion angle distribution near the entrance section and leads to deviation from the theoretical model geometry. Therefore, in the present note we examine the experimental data on a diffuser with thick boundary layer at the entrance, whose geometry corresponds rigorously to the theory (angles $\alpha/2$ do not exceed 9°). /521

We constructed a diffuser of circular cross section with entrance radius r_{w0} = 42.5 mm, calculated for a value of the parameter $\Delta_0^* = 0.1$ with $k = 0.325$. The theoretical initial velocity profile nonuniformity was created by an inlet duct of constant section whose length was determined from the data of [9]. A reservoir was installed ahead of the inlet duct.

In the diffuser testing the measurements were made by the pneumometric technique using the conventional method. The velocity corresponding to the calculated initial flow nonuniformity was refined in the course of the experiment and the constancy of this velocity was monitored on the basis of the pressure drop in the entrance reservoir. The static pressure was measured by means of static pressure taps in the wall, with the axis of the ports being perpendicular to the inner surface of the channel. The velocity profiles $u = u(y/\delta)$ in the boundary layer were investigated at several sections with the aid of a total pressure microprobe mounted on a micropositioner, and these profiles were used as a basis for determining the effective displacement and energy-loss areas. The minimal micropositioner step was 0.02 mm. In the measurement process the discharge equation was satisfied at the various channel sections to within $\pm$ 1%.

The measurement results and the calculated relations are shown in Figure 1. In the figure the distribution of the velocity $u_{\delta i}$ corresponding to ideal fluid channel flow (the ideal case), the distribution of the velocity $\bar{u}_\delta$ (computational case) corresponding to viscous fluid flow with the given initial velocity profile nonuniformity, and also the calculated values of Δ^* and Δ^{***} are compared with the experimental data. Versions a and b correspond to $\mathrm{Re}_0 = r_{w0}\bar{u}_0/\nu = 0.85$ and $1.1 \cdot 10^5$ with a turbulent layer at the entrance. The curves show that the experimental study confirmed the validity of the basic theoretical relations. Small changes in Re_0 had practically no effect on the aerodynamic characteristics. The satisfactory agreement of the theoretical and experimental values for Δ^* and Δ^{***} makes it possible to /522

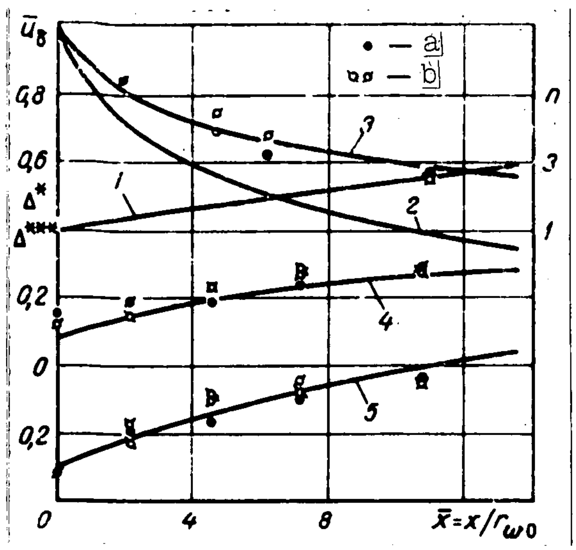

Figure 1. Comparison of calculated and experimental data for diffuser of circular cross section, profiled on the basis of the conditions $\Delta_0^* = 0.1$; $k = 0.325$; $\tau_w = 0$; $1 - n$; $2 - \bar{u}_{\delta i}$; $3 - \bar{u}_\delta$, $\bar{u}_{\delta 1}$; $4 - \Delta^{***}$; $5 - \Delta^*$

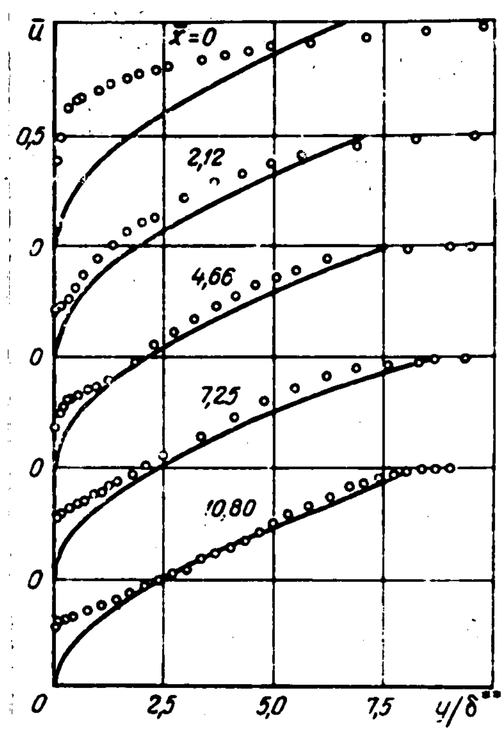

Figure 2. Deformation of velocity profiles in diffuser $(\Delta_0^* = 0.1;\ k = 0.325)$

consider that the calculation yields values of the total pressure loss coefficient ζ which are quite close to the experimental values [2].

The deformation of the velocity profiles in the boundary layer is shown in Figure 2, where we see gradual transition of the flow regime from separation-free at the entrance to the pre-separation type. The deviation of the experimental points from the calculated curves near the wall is apparently the result of measurement errors owing, at least partly, to noncoincidence of the geometric and effective centers of the microtube inlet port.

Modification of the model from the condition k = 0.400 did not improve the channel experimental characteristics (Figure 3).

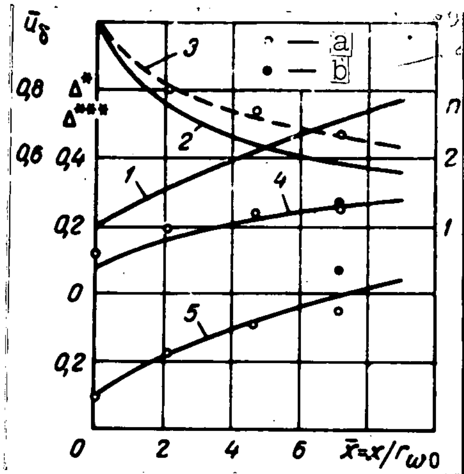

Figure 3. Comparison of calculated and experimental data for diffuser of circular cross section, profiled on the basis of the conditions $\Delta_0^*=0.1$; $k=0.400$; $\tau_w=0$; $1-n$; $2-\bar{u}_\delta$; $3-\bar{u}_{\delta 1}$; $4-\Delta^{***}$; $5-\Delta^*$

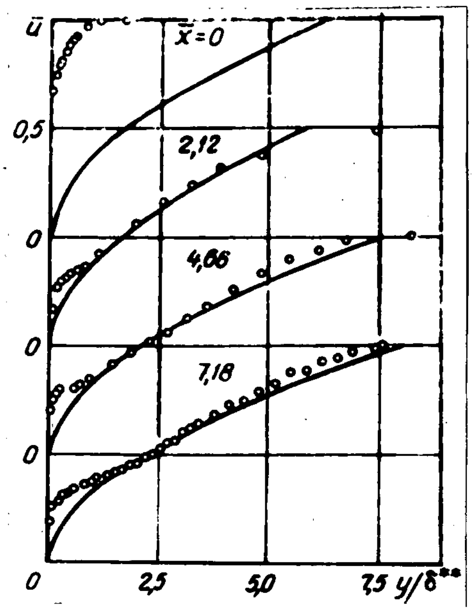

Figure 4. Deformation of velocity profiles in diffuser ($\Delta_0^*=0.1$; $k=0.400$)

The flow in the modified diffuser was accompanied by significant pressure pulsations. As is shown in Figure 3, in this case the theory captures less well the velocity variation along the channel length: the experimental velocity distribution curve $\bar{u}_{\delta 1}(\bar{x})$ deviates markedly from the calculated curve $\bar{u}_\delta(\bar{x})$. The approach to separation was expressed in disruption of flow axisymmetry in the final sections of the diffuser. Therefore, the discharge equation was violated when measuring the displacement area at these sections along a single radius (version a). For $x = x/r_{w0} = 7.2$ we measured the velocity profiles along two mutually perpendicular diameters (version b). In this case the constant discharge condition is satisfied to within 1%. The velocity profiles in the modified diffuser are shown in Figure 4. /523

On the basis of the above discussion, we can consider that the calculation of preseparation diffusers can be made using the formulas of [2], taking the value of the empirical constant $k = 0.325$.

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Nomenclature

x, y are longitudinal and transverse coordinates; r_w, Π, F are the channel radius, perimeter, and cross-section area; n is the diffuser expansion ratio; $\alpha/2$ is half the local expansion angle; δ, ϑ are the boundary layer thickness and area; ϑ^{*}, ϑ^{**}, ϑ^{***} are the displacement, momentum-loss, and energy-loss areas; u_0 is the discharge-average velocity at the channel entrance; $\bar{u}_{\delta i}$, $\bar{u}_{\delta}$, $\bar{u}_{\delta 1}$ are the dimensionless velocities at the channel centerline (in ideal flow, calculated, and experimental); Re is the Reynolds number; ζ is the total pressure loss coefficient; k is an empirical coefficient; τ_w is the wall friction stress. The subscript 0 refers to the entrance section.

Summary

The results of an experimental study of pre-separation circular diffusers, whose geometric and aerodynamic characteristics have been determined on the basis of the semi-empirical method of boundary layer calculation are presented. The predicted and experimental results are shown to be close enough.

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